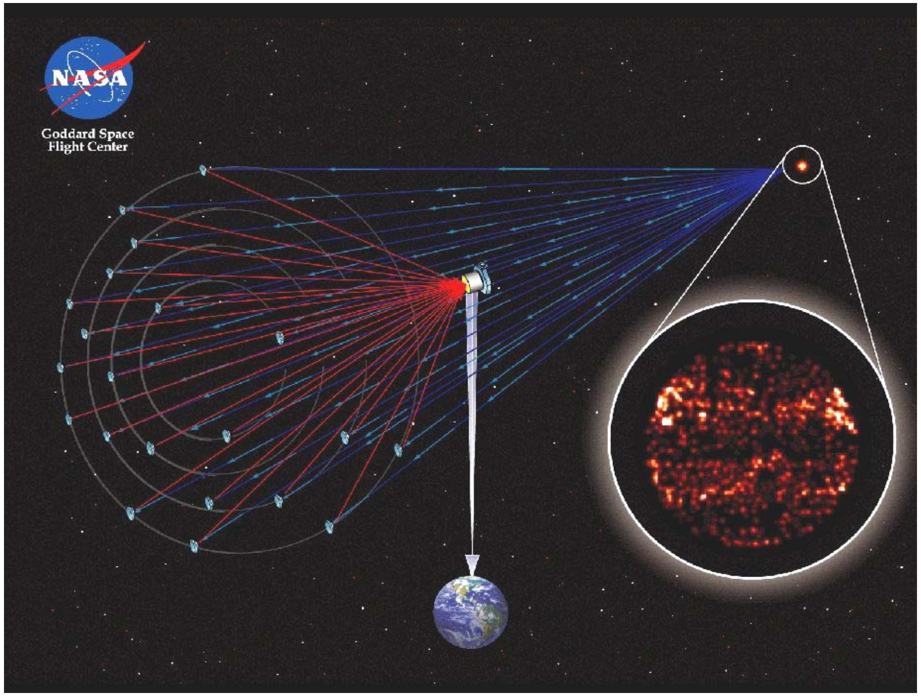
Technology Development for the Stellar Imager (SI) Vision Mission:

Imaging the UV/Optical Universe with Sub-milliarcsec Resolution



K. G. Carpenter (NASA/GSFC), C. J. Schrijver (LMATC), M. Karovska (SAO)
and the SI Mission Concept Development Team

URL: http://hires.gsfc.nasa.gov/si/

June 27, 2006 - ESTC Meeting in Greenbelt, MD

Mission Concept Development Team

- Mission concept under development by NASA/GSFC in collaboration with experts from industry, universities, & astronomical institutes:

Ball Aerospace & Technologies Corp.	Lockheed Martin Adv. Tech. Center
NASA's Jet Propulsion Laboratory	Naval Research Laboratory/NPOI
Northrop-Grumman Space Tech.	Seabrook Engineering
Sigma Space Corporation	Smithsonian Astrophysical Observatory
Space Telescope Science Institute	State Univ. of New York/Stonybrook
Stanford University	University of Colorado at Boulder
University of Maryland	University of Texas/Arlington
European Space Agency	Kiepenheuer Institute
Potsdam Astronomical Institute	University of Aarhus

- Institutional and topical leads from these institutions include:
  - K. Carpenter, C. Schrijver, R. Allen, A. Brown, D. Chenette, D. Mozurkewich, K. Hartman, M. Karovska, S. Kilston, J. Leitner, A. Liu, R. Lyon, J. Marzouk R. Moe, N. Murphy, J. Phillips, E. Stoneking, F. Walter

- Additional science and technical collaborators from these institutions include:
  - T. Armstrong, T. Ayres, S. Baliunas, C. Bowers, G. Blackwood, J. Breckinridge, F. Bruhweiler, S. Cranmer, M. Cuntz, W. Danchi, A. Dupree, M. Elvis, N. Evans, C. Grady, F. Hadaegh, G. Harper, L. Hartman, R. Kimble, S. Korzennik, P. Liewer, R. Linfield, M. Lieber, J. Linsky, M. Marengo, L. Mazzuca, J. Morse, L. Mundy, S. Neff, C. Noecker, R. Reinert, R. Reasenberg, D. Sasselov, E. Schlegel, J. Schou, P. Scherrer, M. Shao, W. Soon, G. Sonneborn, R. Stencel, B. Woodgate

- International Partners include:
  - J. Christensen-Dalsgaard, F. Favata, K. Strassmeier, O. Von der Luehe

The *Stellar Imager (SI)*

is a UV-Optical, space-based interferometer for 0.1 milli-arcsecond spectral imaging of stellar surfaces and interiors and of the Universe in general.

It will resolve for the first time the surfaces of sun-like stars and the details of many other astrophysical objects & processes, e.g.:

Magnetic Processes in Stars
activity and its impact on planetary climates and on the origin and maintenance of life; stellar structure and evolution

Stellar interiors
in stars outside solar parameters

Infant Stars/Disk systems
accretion foot-points, magnetic field structure & star/disk interaction

Hot Stars
hot polar winds, non-radial pulsations, envelopes and shells of Be-stars

Cool, Evolved Giant & Supergiant Stars
spatiotemporal structure of extended atmospheres, pulsation, winds, shocks

Supernovae & Planetary Nebulae
close-in spatial structure

Interacting Binary Systems
resolve mass-exchange, dynamical evolution/accretion, study dynamos

Active Galactic Nuclei
transition zone between Broad and Narrow Line Regions; origin/orientation of jets; distances

SI's Primary Science Goals are to understand:

- Solar and Stellar Magnetic Activity and their impact on Space Weather, Planetary Climates, and Life
- Magnetic Processes and their roles in the Origin and Evolution of Structure and in the Transport of Matter throughout the Universe

See details on SI website at:

http://hires.gsfc.nasa.gov/si/

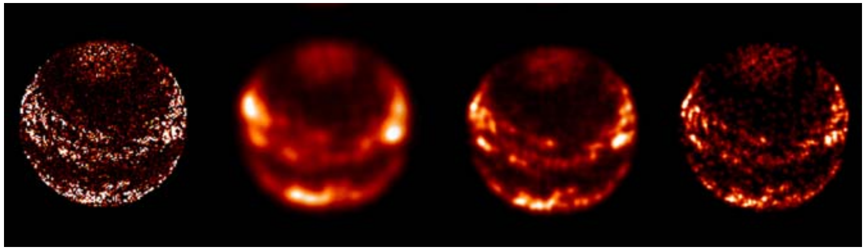
(SPIE 2006 paper or PDF of this ESTC presentation)

Mission and Performance Parameters		
Parameter	**Value**	**Notes**
Maximum Baseline (B)	100 – 1000 m (500 m typical)	Outer array diameter
Effective Focal Length	1 – 10 km (5 km typical)	Scales linearly with B
Diameter of Mirrors	1 - 2 m (1 m currently)	Up to 30 mirrors total
λ-Coverage	UV: 1200 – 3200 Å Optical: 3200 – 5000 Å	Wavefront Sensing in optical only
Spectral Resolution	UV: 10 Å (emission lines) UV/Opt: 100 Å (continuum)	
Operational Orbit	Sun-Earth L2 Lissajous, 180 d	200,000x800,000 km
Operational Lifetime	5 yrs (req.) – 10 yrs (goal)	
Accessible Sky	Sun angle: $70^\circ \leq \beta \leq 110^\circ$	Entire sky in 180 d
Hub Dry Mass	1455 kg	Possibly 2 copies
Mirrorsat Dry Mass	65 kg (BATC) - 120 kg (IMDC)	For each of up to 30
Ref. Platform Mass	200 kg	
Total Propellant Mass	750 kg	For operational phase
Angular Resolution	50 μas – 208 μas (@1200–5000Å)	Scales linearly ~ λ/B
Typical total time to image stellar surface	< 5 hours for solar type < 1 day for supergiant	
Imaging time resolution	10 – 30 min (10 min typical)	Surface imaging
Seismology time res.	1 min cadence	Internal structure
# res. pixels on star	~1000 total over disk	Solar type at 4 pc
Minimum FOV	> 4 mas	
Minimum flux detectable at 1550 Å	5.0×10^{-14} ergs/cm^2/s integrated over C IV lines	10 Å bandpass
Precision Formation Fly.	s/c control to mm-cm level	
Optical Surfaces Control	Actuated mirrors to μm-nm level	
Phase Corrections	to λ/10 Optical Path Difference	
Aspect Control/Correct.	3 μas for up to 1000 sec	Line of sight maintenance

What Will Stellar Imager See?

Solar-type star at *4 pc* in *CIV line*

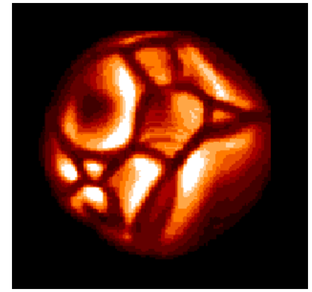
Model ***SIsim* images**



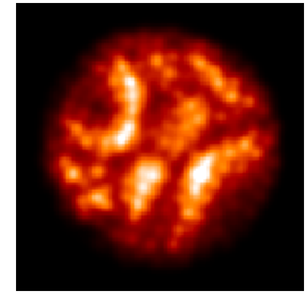
Baseline: 125m **250m** **500 m**

Evolved giant star at *2 Kpc* in *Mg H&K line*

Model

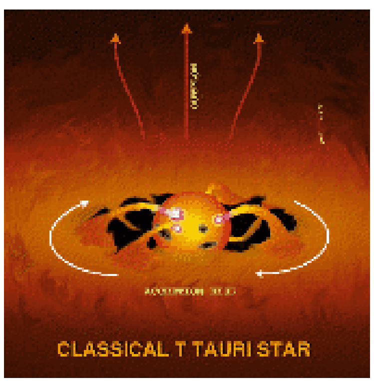


***SIsim* image (2mas dia)**

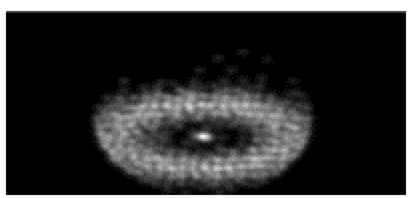


Baseline: 500 m

SI imaging of planet forming environments: magnetosphere-disk interaction region



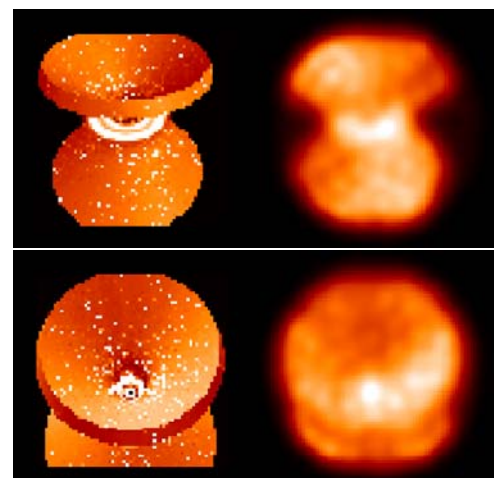
0.1 mas



***SI* simulation in Ly α–fluoresced H2 lines**

Baseline: 500 m

SI imaging of nearby AGN will differentiate between possible BELR geometries & inclinations



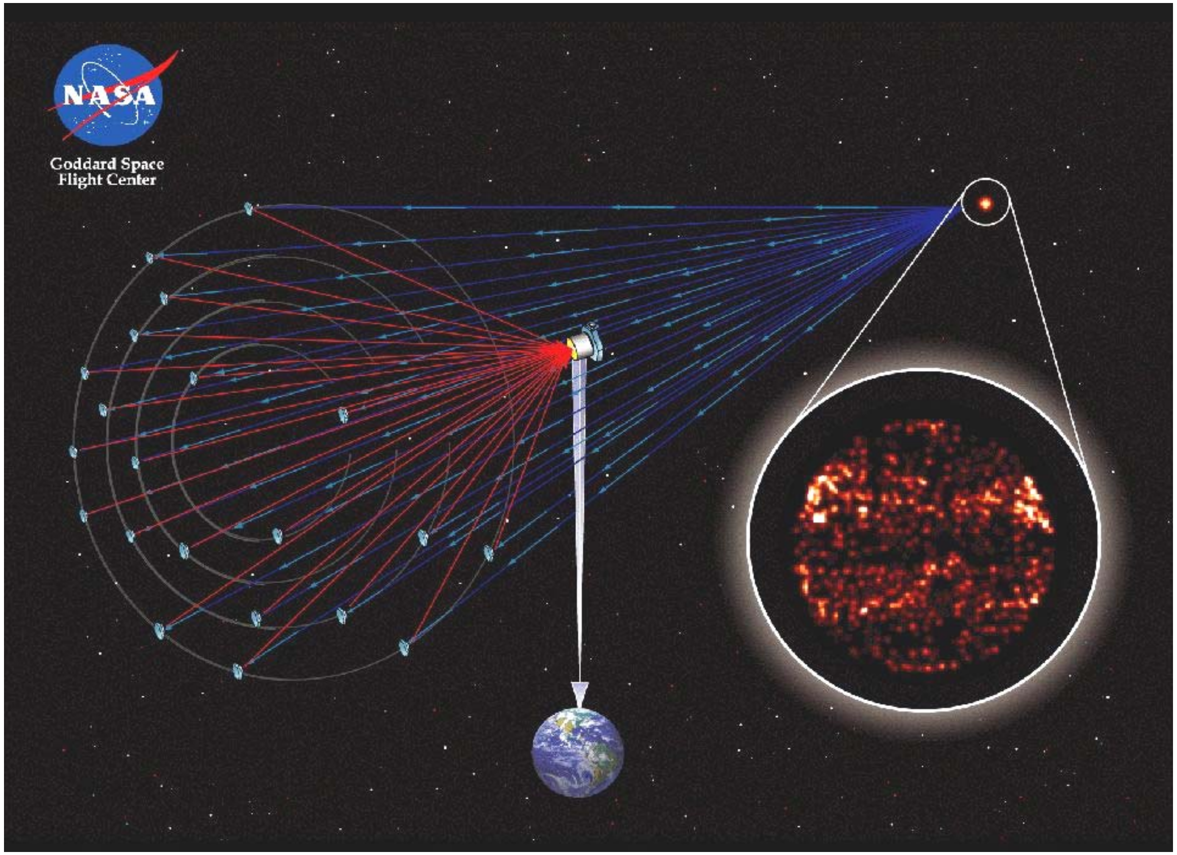
0.1 mas

model ***SI* simulations in *CIV line* (500 m baseline)**

Required Capabilities for SI

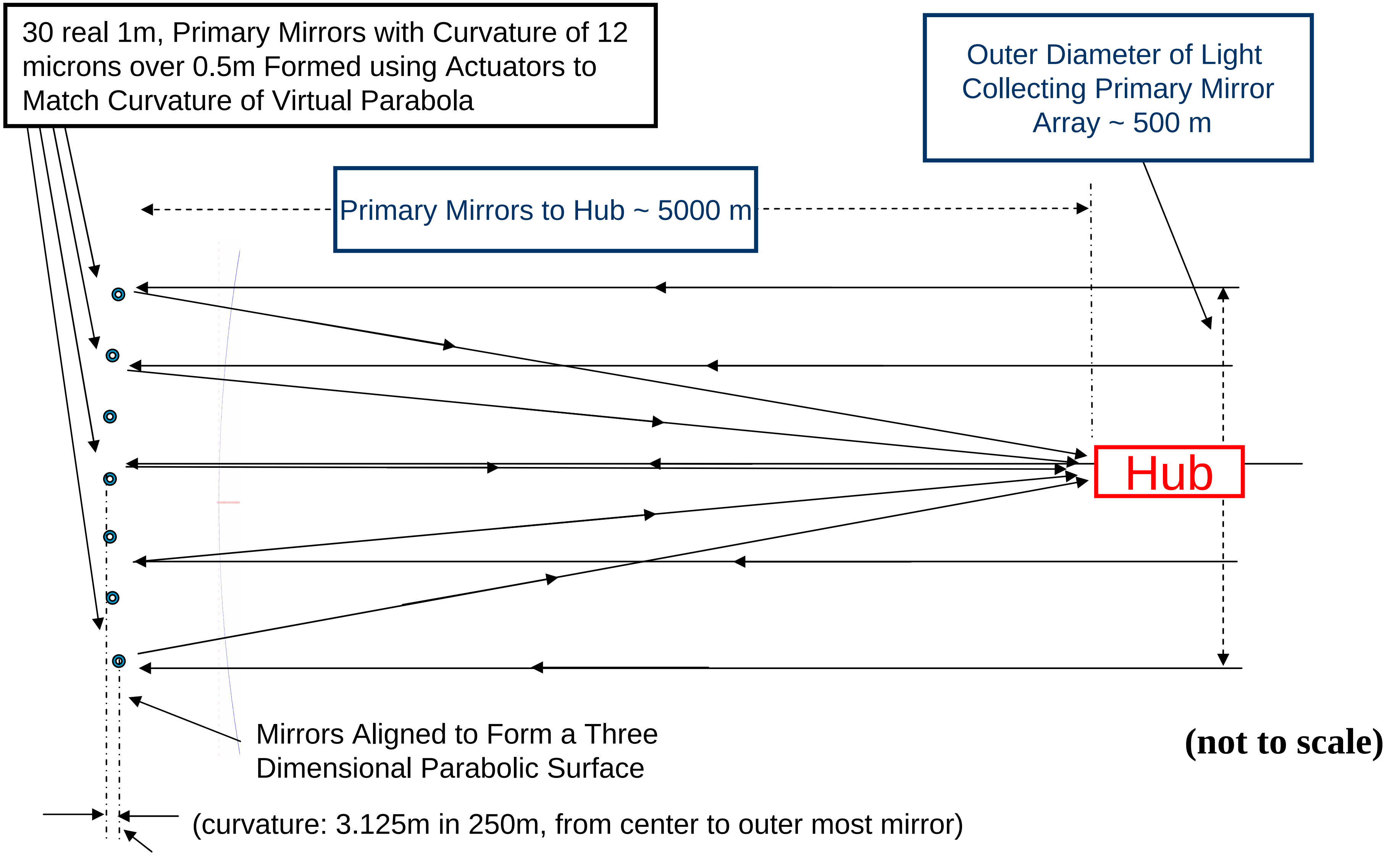
- Wavelength coverage: 1200 – 5000 Å
- access to UV emission lines from Ly α 1216 Å to Mg II 2800 Å for stellar surface imaging
  - Important diagnostics of most abundant elements
  - much higher contrast between magnetic structures and background
  - smaller baselines (UV save 2-4x vs. optical, active regions 5x larger)
  - ~10-Å UV pass bands, e.g. C IV (100,000 K); Mg II h&k (10,000 K)
- broadband, near-UV or optical (3,000-10,000 K) for high time resolution spatially-resolved asteroseismology to resolve internal structure
- angular resolution of 50 micro-arcsec at 1200 Å (120 mas @2800 Å)
- ~1000 pixels of resolution over the surface of nearby dwarf stars
- enable energy resolution/spectroscopy of detected structures
- a long-term (~ 10 year) mission to study stellar activity cycles:
  - individual telescopes/hub(s) can be refurbished or replaced

“Strawman” Concept

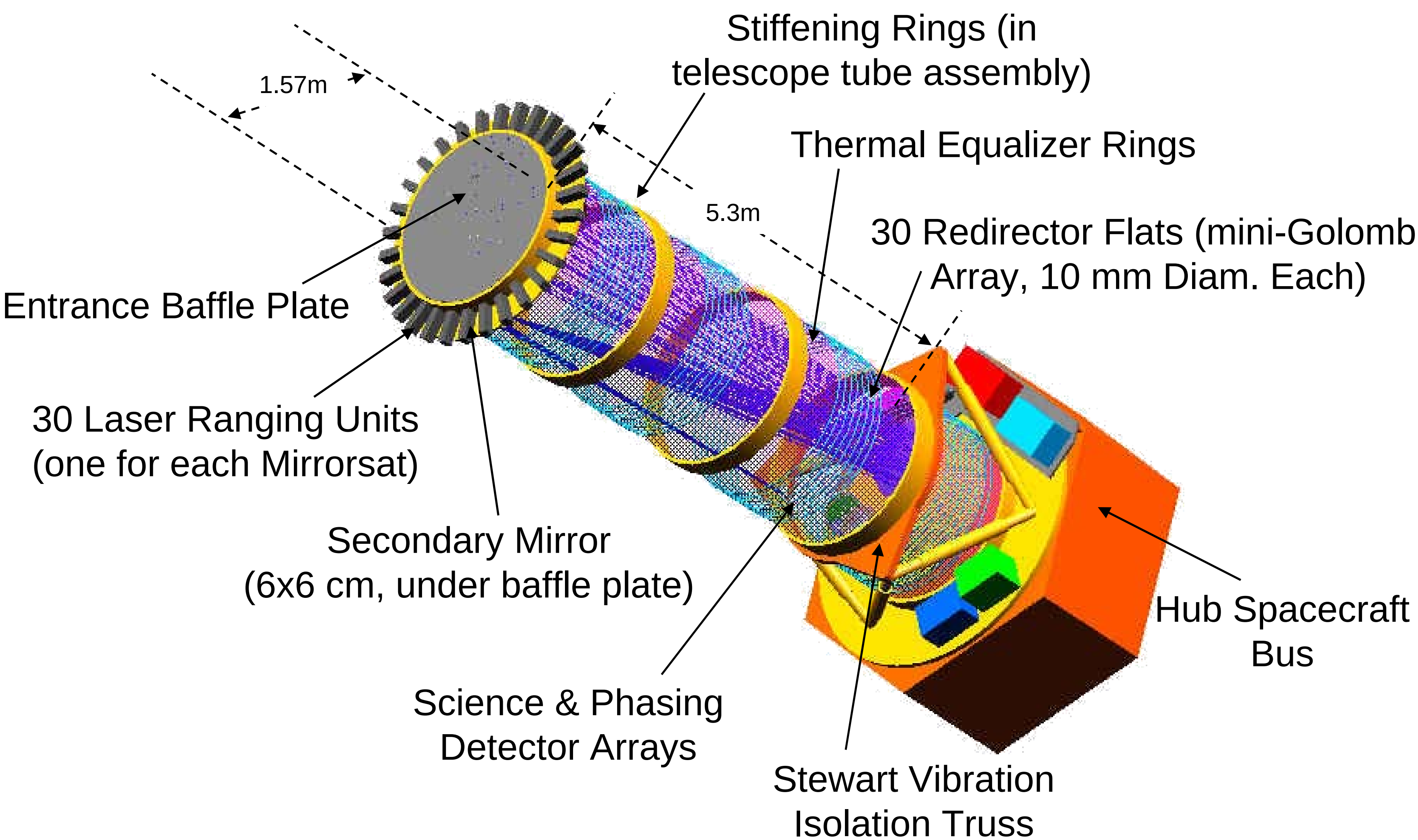


- a 0.5 km diameter space-based UV-optical Fizeau Interferometer
- located near Sun-earth L2 to enable precision formation flying
- 20-30 primary mirror elements focusing on beam-combining hub
- large advantages to flying more than 1 hub:
  - critical-path redundancy & major observing efficiency improvements

SI Cross-Sectional Schematic

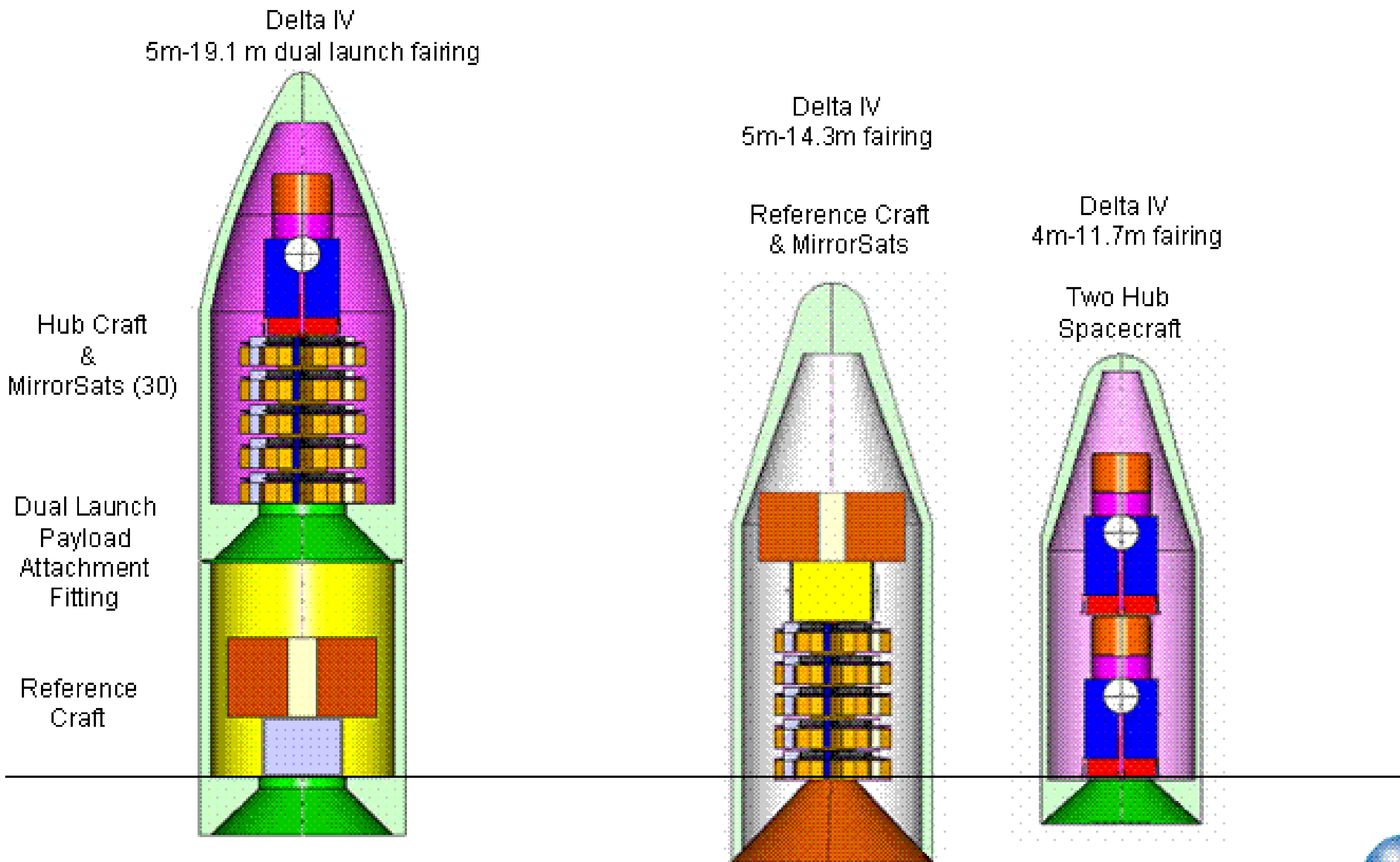


Principal Elements of SI Hub



Launch Configuration
Dual vs. Single Launch

Integrated Mission Design Center



4-7 Oct 2004
SI-VM

Sensitive Information
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Mechanical, p3
Final Version

Top Technological Challenges and Enabling Technologies

- **formation-flying of ~ 30 spacecraft**
  - deployment and initial positioning of elements in large formations
  - real-time correction and control of formation elements
    - staged-control system (km → cm → nm)
  - aspect control to 10's of micro-arcsec
  - positioning mirror surfaces to 2 nm
  - variable, non-condensing, continuous micro-Newton thrusters
- **precision metrology** (2 nm over multi-km baselines)
  - multiple modes to cover wide dynamic range
- **wavefront sensing and real-time, autonomous analysis**
- **methodologies for ground-based validation of distributed systems**
- **additional challenges**
  - mass-production of "mirrorsat" spacecraft: cost-effective, high-volume fabrication, integration, & test
  - long mission lifetime requirement
  - light-weight UV quality mirrors with km-long radii of curvature (perhaps using deformable UV quality flats)
  - larger format (6 K x 6 K) energy resolving detectors with finer energy resolution (R=100)

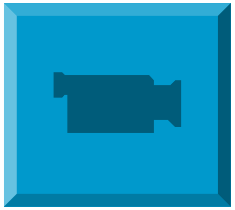
Development of Precision Formation Flying Algorithms

Eric Stoneking (GSFC)

- Micrometer-level formation-flying algorithms successfully demonstrated in simulation
  - **First stage: Formation Acquisition using only omni-directional radio-frequency ranging sensors for relative position determination.** Formation acquisition has been successfully demonstrated assuming noiseless range measurements. Modifications in work to improve robustness to sensor noise.
  - **Second stage: Laser Metrology Acquisition.** This control stage closes a control loop around laser ranging measurements to control relative hub-mirror range to the micrometer level, as well as transverse position control to the 10-cm level. This acquisition stage has been successfully demonstrated in simulation, including the effects of sensor noise and non-ideal thrusters.
  - **Third Stage: Coarse Spot Acquisition.** Using sensors on the aperture plate of hub spacecraft, steer target starlight into the aperture and onto the detector. Successfully simulated.
  - **Fourth Stage: Fine Spot Acquisition:** Feeding back the spot location on the detector, steer target starlight to center of the detector. Successfully simulated (neglecting spot confusion).
- The Next Steps
  - Management of multiple spots on the detector. Incorporating lessons learned, develop strategies to avoid confusion of multiple spots.
  - Incorporate optical wave sensor acquisition. Using OSCAR software to simulate a wavefront sensor, develop fine formation-flying algorithms based on wavefront feedback.

Demonstration of Precision Formation Flying Controls

- **Movie shows simulation of 500-m focal length, 50-m aperture, 7 s/c system going through initial phase of acquisition process, incl. alignment to Sun and to science target**
  (actual computation, not just a movie!)
  - **Scene 1: Hub rotates into proper orientation to Sun**
  - **Scene 2: Mirrorsats acquire ~ attitude via RF ranging**
  - **Scene 3: Mirrorsats take up stations (RF), acquire laser link**
  - **Scene 4: Hub View, as laser links settle in (red), acquisition photosensors detect target light (blue), target light into apertures (white)**
    - Performance shown uses laser ranging and coarse cross-axis measurements and star-tracker-quality attitude determination. Feedback from target light not yet implemented (finer stages).



The GSFC/MSFC/MIT Synthetic Imaging Formation Flying Testbed (SIFFT):

K. Carpenter, R. Lyon, K. Hartmann/GSFC; P. Stahl/MSFC, D. Miller/MIT,
J. Marzouk/Sigma Space, D. Mozurkewich/Seabrook Eng.

- **A ground-based testbed which will**
  - In combination with FIT enable synergistic development of technologies needed to support space-borne synthetic aperture ultra-high resolution imaging
  - Develop and demonstrate algorithms for autonomous precision formation flying which can, in the future, be combined with higher precision optical control systems
  - Set requirements for future staged-control systems
  - Be created at relatively low cost by utilizing equipment from existing MIT-developed SPHERES (**S**ynchronized **P**osition **H**old **E**ngage and **R**eorient **E**xperimental **S**atellites) experiment on the MSFC Flat Floor Facility
  - Areas of investigation include:
    - Formation Capture (deployment)
    - Formation Maintenance
    - Formation Reconfiguration
    - Synthetic Imaging maneuvers (retargeting & reconfiguration)

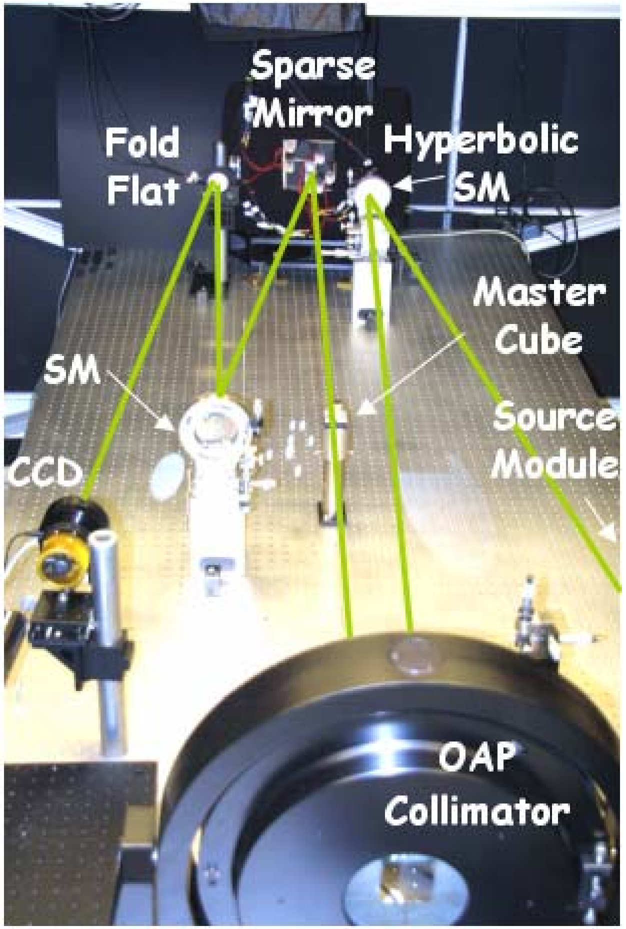
One SPHERES unit

Five SPHERES on air carriages on MSFC Flat Floor

The GSFC Fizeau Interferometer Testbed (FIT):
Developing Closed-Loop Optical Control for Large Arrays

K. Carpenter, R. Lyon, A. Liu, K. Hartman/GSFC; D. Mozurkewich/Seabrook Eng., P. Petrone, P. Dagoda, P. Liiva, D. Reed, J. Marzouk/Sigma Space, T. Armstrong & X. Zhang/NRL, L. Mundy/UMD

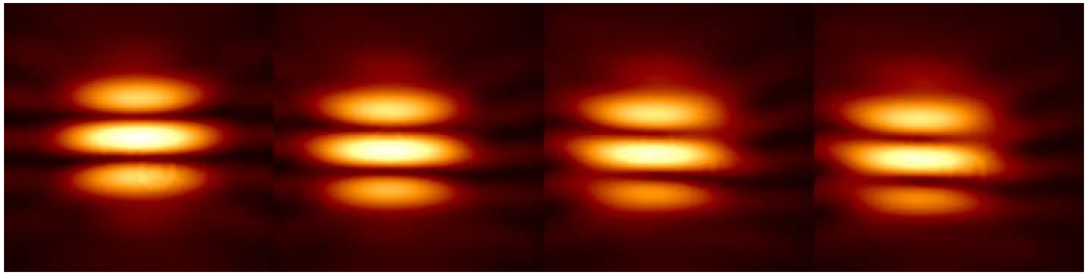
- **A ground-based testbed to:**
  - explore principles of and requirements for Stellar Imager & other Fizeau Interferometer/Sparse Aperture Telescopes (e.g. MAXIM, LF, PI), enable their development, reduce technical and cost risks
  - utilize 7-18 separate articulated apertures, with tip, tilt, and piston automatically controlled on each
  - validate new and existing analytic and computational models to ensure realistic performance assessment of future flight designs
  - demonstrate closed-loop control of system based on analysis of science data stream
  - evaluate and demonstrate performance of new and existing image synthesis algorithms and successful image reconstruction from actual laboratory sparse aperture/interferometric data



Early FIT Results
Rick Lyon, Alice Liu (GSFC)

- **Phase retrieval code developed for wavefront sensing from 7 apertures. Code solves for wavefront (WF) piston, tip & tilt over the set of apertures.**
- **The WF piston, tip and tilt needs to be converted to actuator voltages which drive mirror piston, tip and tilt.** There is not a one-to-one mapping between WF piston, tip and tilt and actuator voltages and significant hysterisis requires a control approach based upon forward and backward response matrices - the matrix is different depending on direction of actuator motion.
- **To determine the response matrices ~8000 broadband images have been collected of an unresolved point source** with all apertures masked except for 2. One is held fixed (reference) and the other moved in 1 degree of freedom (DOF) over the range of +/- 300 nm in 6 steps in a sawtooth pattern for ~330 cycles. The difference in what was commanded and what was sensed over many cycles allows the determination of the response matrices.

Partial sequence of images as one actuator is moved to tilt a single actuated mirror in a diagonal direction. The images become progressively more de-phased from left to right; the fringes are less sharp and become more distorted as we move from the best aligned position of the leftmost image.

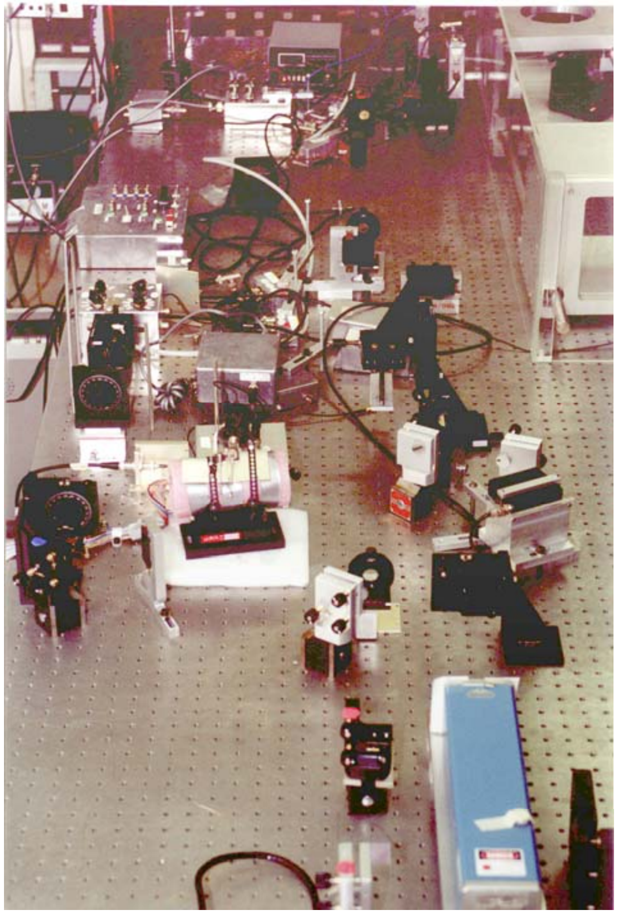


SAO Metrology Testbed:
Developing a Tracking Frequency Gauge

J. Phillips, R. Reasenberg, M. Karovska/SAO

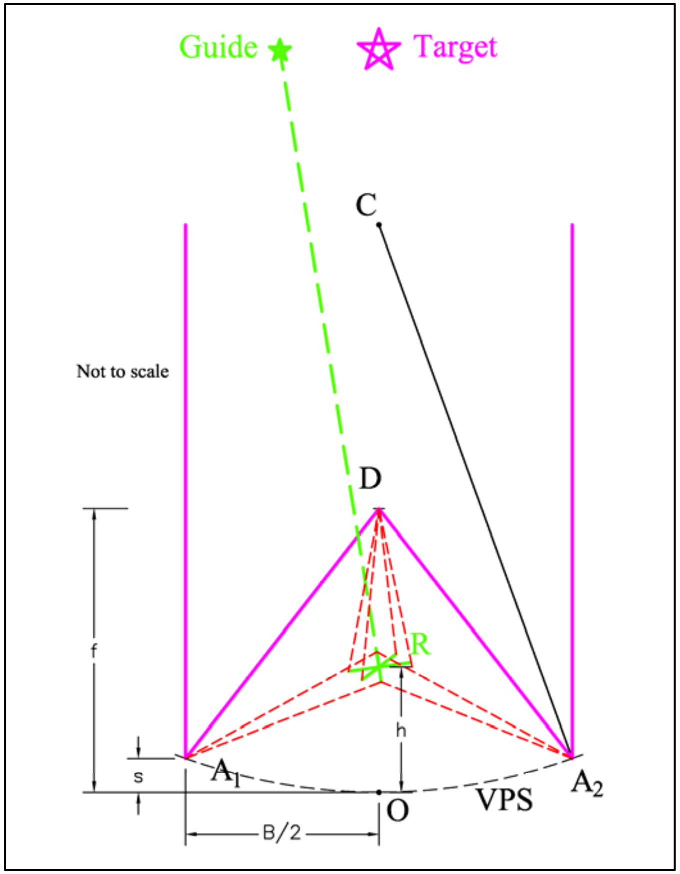
- **A ground-based testbed to:**
  - Explore simplified laser gauge architecture
  - Utilize rugged, fiber-coupled *telecomm* parts
    - 1550 nm, distributed feedback (DFB) semiconductor lasers, isolators, beamsplitters
    - Laser presently flying in ACE, on SCISAT
  - Validate this low-cost approach
  - Demonstrate with semiconductor lasers*
    - Bandwidth ≥ 50 kHz
    - 3D incremental to 1 picometer, 1 to 10000 s
    - 3D absolute to ~λ/10
  - * Demonstrated in previous (HeNe) version
    - 50 kHz bandwidth
    - 1D incremental to 2 picometer, 1 to 300 min
    - 1D absolute to 0.1 mm

Testbed for HeNe version



A Metrology Architecture for SI

- Guide star (V<7.5) within 2° of target
- Reference platform (R) aligned with guide star to within 1 arcsec, measures guide star offset to 1 micro-arcsec
- Platform contains fiducial points and laser gauges to tie guide star measurement to the detector hub (D) and mirrorsats, meeting SI's pointing requirement
- Optical truss end points joined by multi-beam launcher and shared target retroreflectors



(Demonstration) Pathfinder Mission

- A pathfinder mission which takes smaller technological steps is desirable to reduce mission risk and would
  - advance technologies needed for other missions in NASA strategic plans
  - will address a subset of the SI science goals

Desirable characteristics of a pathfinder mission

- possible within a decade
- uses a modest number of free-flying spacecraft (3-5)
- operates with modest baselines (~ 20-50 m) and a resolution of ~ 1 milli-arcsec
- performs beam combination with ultraviolet light
- produces UV images via imaging interferometry and enable significant new science

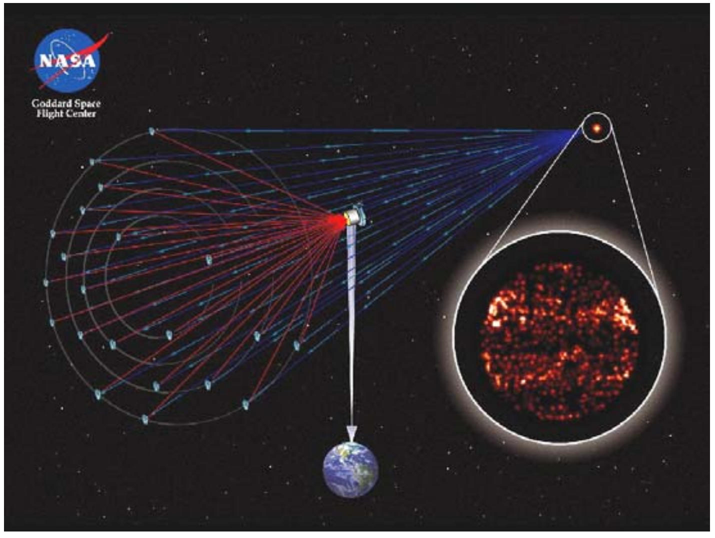
- Such a mission with a small # of spacecraft
  - requires frequent reconfigurations and limits observations to targets whose variability does not preclude long integrations
  - tests most of the technologies needed for the full-size array

SI Status

- SI in NASA SEC (now SSSC) Roadmap since 2000
- SI selected for further concept development by the NASA HQ 2003 Vision Mission NRA review
- Major Partnerships established with LMATC, SAO, BATC, NGST, JPL, CU to develop concept/technology
- Phase I of the Fizeau Interferometry Testbed (FIT) has begun operation to develop closed-loop optical control of a multi-element array
- GSFC Integrated Mission Design Center (IMDC) and Instrument Synthesis and Analysis Lab (ISAL) studies executed (10/2004; 2/2005) to produce a system design & technology development roadmap
- SI presented to SEU/Origins, SSSC, APIO, Universe Roadmap Committees (Nov. 2005 →)
- **In the May, 2005 NASA Strategic Roadmaps, SI is included as**
  - **A “Flagship” (Vision) mission in the SSSC Roadmap**
  - **A candidate “Pathways to Life Observatory” in the EUD Roadmap**

Summary: Stellar Imager (SI) Vision Mission

- UV-Optical Interferometer to provide 0.1 mas imaging (+ spectroscopy) of
  - magnetic field structures that govern: formation of stars & planetary systems, habitability of planets, space weather, transport processes on many scales in Universe
- 20-30 “mirrorsats” formation-flying with beam combining hub
- Launch ~ 2024, to Sun-earth L_2
- maximum baseline ~500 m
- => 1000 pixels/stellar image
- Mission duration: ~10 years



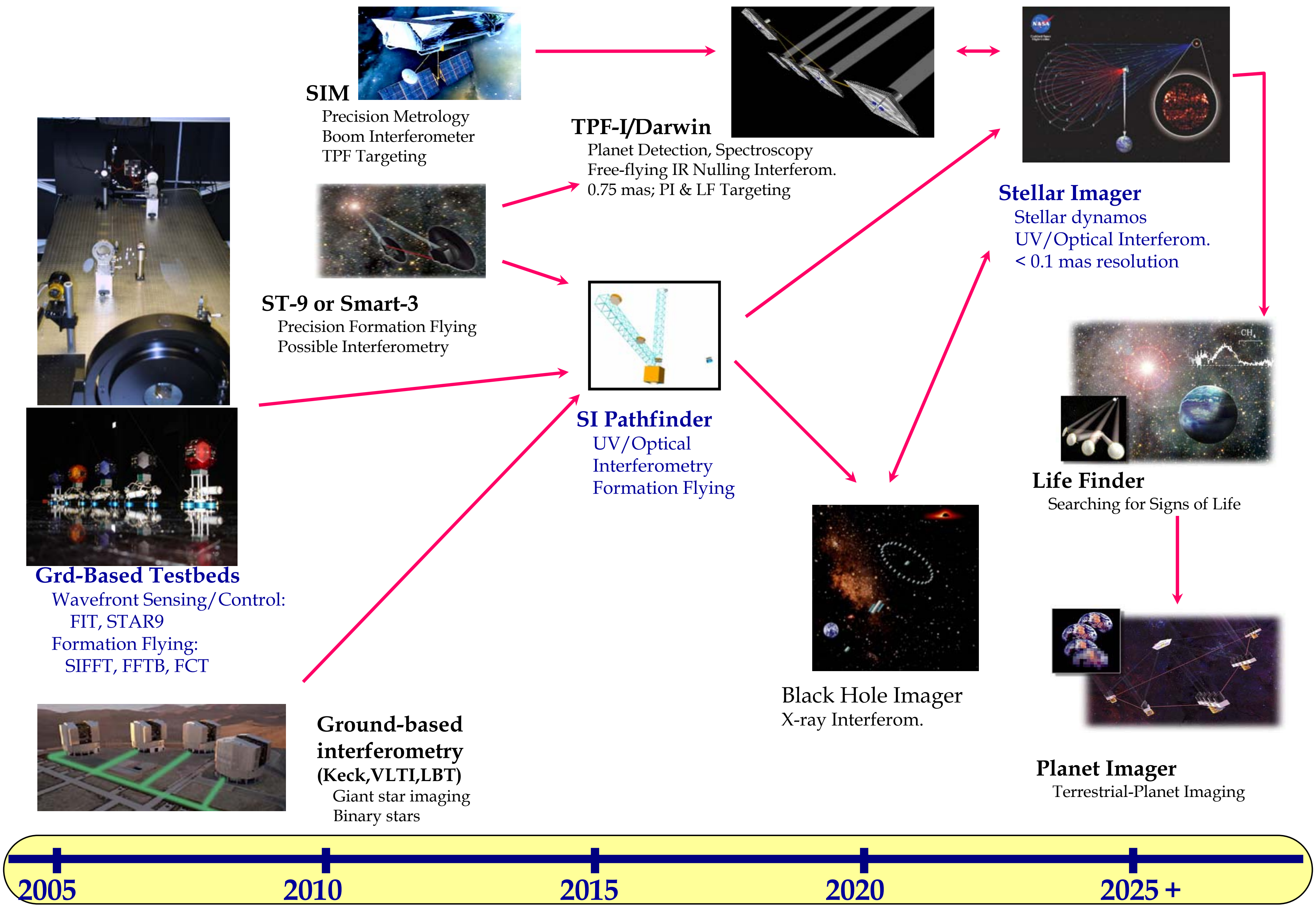
http://hires.gsfc.nasa.gov/si/

Prime Science Goals

- **image surface/sub-surface features of distant stars; measure their spatial/temporal variations to understand the underlying dynamo process(es)**
- **improve long-term forecasting of solar and stellar magnetic activity**
- **understand the impact of stellar magnetic activity on planetary climates and life**
- **understand transport processes controlled by magnetic fields throughout the Universe**
- **perform high angular resolution studies (imaging + spectroscopy) of Active Galactic Nuclei, Quasars, Supernovae, Interacting Binary Stars, Forming Stars/Disks**

Extra slides

Development of Space Interferometry



SI and the NASA-ESA Strategies

- ***SI*** addresses the origins & evolution of structure & life in the Universe, and specific science goals of 3 research Themes in the NASA SMD
  - learn how galaxies, stars, planetary systems form & evolve (Origins/EUD)
  - understand development of structure/flows of magnetic fields (SEU/EUD)
  - understand origins & societal impacts of variability in Sun-Earth System (SSSC)
- ***SI*** complements the planetary imaging interferometers
  - ***Terrestrial Planet Finder-I (TPF-I)/Darwin*** and ***Planet Imager*** null the stellar light to find and image planets
  - ***Stellar Imager*** images the central star to study the effects of that star on the habitability of planets and the formation of life on them.
- ***SI*** is on the strategic path of NASA Origins interferometry missions and is a stepping stone towards crucial technology…
  - comparable in complexity to the ***Terrestrial Planet Finder-I***
  - will serve as technological & operational pathfinder for ***Life Finder (LF) and Planet Imager (PI)***

TPF/Darwin, SI, LF, and **PI** together provide complete views of other solar systems

Stellar Imager and the President's Vision

SI fits into the President's Exploration Initiative in 2 distinct arenas:

1) as one of the "deep-space observatories" which will be a part of the search for and study of habitable planets around other stars.

Stellar Imager (SI) is an essential part of this mandate since it enables the assessment of the impact of stellar magnetic activity on the habitability of planets found by the planet search and imaging missions (e.g., TPF and Planet Imager (PI)).

2) as a means to improve our ability to forecast space weather within our own solar system:

Exploration requires that we know space weather throughout much of the heliosphere, and that means we need long-term forecasts of solar activity, which in turn requires a fundamental understanding of the solar dynamo and of all related transport processes. The Living With a Star initiative addresses that on the fairly short term, while the Stellar Imager is to provide the knowledge (constraints from a broad population of stars of differing activity level) critically needed to test and validate models developed under the LWS program.